

Logical operation of one-dimensional photonic crystal based on series and parallel connection

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In this paper, we have proposed the compound structure of one-dimensional photonic crystal (PC), which includes series connection and parallel connection PC. We have studied the transmission characteristics of series connection and parallel connection PC, and obtained some new results. In addition, we have proved the series connection one-dimensional PC can realize the logical AND operation, and the parallel connection one-dimensional PC can realize the logical OR operation. The compound structure of one-dimensional PC can design more new type structure optical devices, and will provide the basic for designing quantum computer.

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Keywords: PC; series connection; parallel connection; logical operation; quantum computer

1. Introduction

E. Yablonovitch and S. John had pointed out that the behavior of photons in 1987. It can be changed when propagating in the material with periodical dielectric constant, and termed such material PC [1,2]. PC important characteristics are: photon band gap, defect states, Light localization and so on. These characteristics make it able to control photons, so it may be used to manufacture some high performance devices which have completely new principles or can not be manufactured before, such as high-efficiency semiconductor lasers, light emitting diodes, wave guides, optical filters, high-Q resonators, antennas, frequency-selective surface, optical wave guides and sharp bends [3-4], WDM-devices [5-6], splitters and combiners [7]. optical limiters and amplifiers [8-10]. The research on PC will promote its application and development on integrated photoelectron devices and optical communication. To investigate the structure and characteristics of band gap, there are many methods to analyze PC including the plane-wave expansion method [11], Greens function method, finite-difference time-domain method [12-14] and transfer matrix method [15-20].

In this paper, we have proposed the compound structure one-dimensional PC, which include series connection, parallel connection compound structure PC. We have studied their transmission characteristics and given the relation of logical operation. The work frequency of light signal is taken as the defect mode frequency of PC. When the PC has the defect mode, transmissivity $T = 1$ corresponds to logical 1. When the PC has no defect mode, transmissivity $T = 0$ corresponds to logical 0. We can find the series connection one-dimensional PC can realize the AND operation, and the parallel connection one-dimensional PC can realize the OR operation. The compound structure PC will help to design more new type structure optical devices, and provide the basic for designing quantum computer.

2. Transfer matrix and transmissivity of one-dimensional PC

For one-dimensional PC, the calculations are performed using the transfer matrix method [21], which is the most effective technique to analyze the transmission properties of PC. For the medium layer i , the transfer matrices M_i for TE wave is given by [21]:

$$M_i = \begin{pmatrix} \cos \delta_i & -i \sin \delta_i / \eta_i \\ -i \eta_i \sin \delta_i & \cos \delta_i \end{pmatrix}, \quad (1)$$

where $\delta_i = \frac{\omega}{c} n_i d_i \cos \theta_i$, c is speed of light in vacuum, θ_i is the ray angle inside the layer i with refractive

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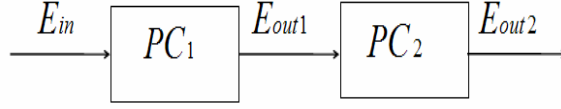


FIG. 1: The series connection structure one-dimensional PC.

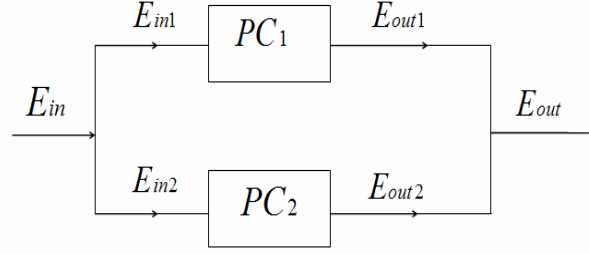


FIG. 2: The parallel connection structure one-dimensional PC.

index $n_i = \sqrt{\varepsilon_i \mu_i}$, $\eta_i = \sqrt{\varepsilon_i / \mu_i} \cos \theta_i$, $\cos \theta_i = \sqrt{1 - (n_0^2 \sin^2 \theta_0 / n_i^2)}$, in which n_0 is the refractive index of the environment wherein the incidence wave tends to enter the structure, and θ_0 is the incident angle.

The total transfer matrix M for an N period structure is given by:

$$\begin{aligned} \begin{pmatrix} E_1 \\ H_1 \end{pmatrix} &= M_B M_A M_B M_A \cdots M_B M_A \begin{pmatrix} E_{N+1} \\ H_{N+1} \end{pmatrix} \\ &= M \begin{pmatrix} E_{N+1} \\ H_{N+1} \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} E_{N+1} \\ H_{N+1} \end{pmatrix}, \end{aligned} \quad (2)$$

where

$$M = \begin{pmatrix} A & B \\ C & D \end{pmatrix}, \quad (3)$$

with the total transfer matrix M , we can obtain the transmissivity T , it is

$$T = \left| \frac{E_{N+1}}{E_1} \right|^2 = \left| \frac{2\eta_0}{A\eta_0 + B\eta_0\eta_{N+1} + C + D\eta_{N+1}} \right|^2. \quad (4)$$

Where $\eta_0 = \eta_{N+1} = \sqrt{\frac{\varepsilon_0}{\mu_0}} \cos \theta_0$. By the Eqs. (1) and (4), we can calculate the transmissivity of one-dimensional PC.

3. Series connection and parallel connection one-dimensional PC transmissivity

Two or multiple one-dimensional PC can be connected by optical fiber, which can be designed series connection, parallel connection compound structure one-dimensional PC. The FIGs. 1 and 2 are series connection and parallel connection one-dimensional PC structures, respectively. The PC_1 and PC_2 are the one-dimensional PC, E_{in} is the input electric field intensity, and E_{out1} and E_{out2} are the output electric field intensity of PC_1 and PC_2 .

(1) The total transmission coefficient t and transmissivity T of series connection one-dimensional PC are

$$t = \frac{E_{out2}}{E_{in}} = \frac{E_{out2}}{E_{out1}} \cdot \frac{E_{out1}}{E_{in}} = t_2 \cdot t_1, \quad (5)$$

$$T = |t|^2, \quad (6)$$

where $t_2 = E_{out2}/E_{out1}$ and $t_1 = E_{out1}/E_{in}$ for the transmission coefficients of PC_1 and PC_2 .

Similarly, we can obtain the transmission coefficient for n series connection PC, such as PC_1, PC_2, \dots, PC_n series connection transmission coefficient is

$$t = t_n \cdot t_{n-1} \cdots t_1. \quad (7)$$

(2) The total transmission coefficient t and transmissivity T of parallel connection one-dimensional PC are

$$t_{\pm} = \frac{E_{out}}{E_{in}} = \frac{E_{out1} \pm E_{out2}}{E_{in}} = \frac{t_1 E_{in1} \pm t_2 E_{in2}}{E_{in}}, \quad (8)$$

when E_{out1} and E_{out2} phase are the same (opposite), the numerator of Eq. (8) takes $+$ ($-$).

when $t_1 = t_2 = t$, there are

$$t_+ = t_1 = t_2 = t, \quad t_- = \frac{t(E_{in1} - E_{in2})}{E_{in}} = t(c_1 - c_2), \quad (9)$$

where $c_1 = E_{in1}/E_{in}$ and $c_2 = E_{in2}/E_{in}$.

when $t_1 \neq t_2$, there is

$$t_+ = c_1 t_1 + c_2 t_2, \quad t_- = c_1 t_1 - c_2 t_2 \quad (c_1 + c_2 = 1). \quad (10)$$

Similarly, the total transmission coefficient of n PC PC_1, PC_2, \dots, PC_n parallel connection is

$$\begin{aligned} t_{\pm} &= \frac{E_{out}}{E_{in}} = \frac{E_{out1} \pm E_{out2} \pm \cdots \pm E_{outn}}{E_{in}} \\ &= \frac{t_1 E_{in1} \pm t_2 E_{in2} \pm \cdots \pm t_n E_{inn}}{E_{in}} \\ &= c_1 t_1 \pm c_2 t_2 \pm \cdots \pm c_n t_n. \end{aligned} \quad (11)$$

4. Numerical result

In this section, we report our numerical results of compound structure one-dimensional PC, the PC PC_1 and PC_2 are constituted by media A and B . The main parameters are: the medium A refractive indices $n_a = 2.45$, thickness $a = 469nm$, the medium B refractive indices $n_b = 1.35$, thickness $b = 890nm$, the center frequency $\omega_0 = \frac{\pi c}{(n_a a + n_b b)} = 4.01 \times 10^{14} Hz$, the incident angle $\theta_0 = 0$.

Firstly, we study the transmission characteristics of series connection and parallel connection structure PC, which are constituted by PC_1 and PC_2 , their structure are $(AB)^{12}$. In PC_1 , the medium B thickness $b = 890nm$. In PC_2 , the medium B thickness $b = 560nm$, which are shown in FIGs. 1 and 2. The series connection and parallel connection structure are referred to as $PC_1 \cdot PC_2$ and $PC_1 + PC_2$. From Eqs. (5) and (6), we can calculate the series connection structure transmissivity. By Eq. (10), we can calculate the parallel connection structure transmissivity $|t_+|^2$.

The FIG. 3 (a), (b), (c) and (d) are the transmissivity corresponding to the structure $PC_1, PC_2, PC_1 \cdot PC_2$ and $PC_1 + PC_2$. From FIG. 3 (a), (b) and (c), we can obtain some results about the series connection PC: (1) The forbidden band width of series connection PC becomes more wider, and it is the union of corresponding forbidden band of part PC PC_1 and PC_2 , which is similar as the series connection ohm law in circuit. (2) We can obtain the more wider forbidden band by PC series connection. (3) With the number of series connection PC increasing, the total width of forbidden band increase. From FIG. 3 (a), (b) and (d) ($c_1 = 0.5$). We can find when coefficient $c_1 = 0.5$ the forbidden band of parallel connection (FIG. 3 (d)) is the intersection of corresponding forbidden band of PC_1 and PC_2 .

Secondly, we begin to study the AND logical operation. In FIGs. 4, 5 and 6, we study the AND operation by the series connection one-dimensional PC PC_1 and PC_2 . The work frequency of light signal is taken as

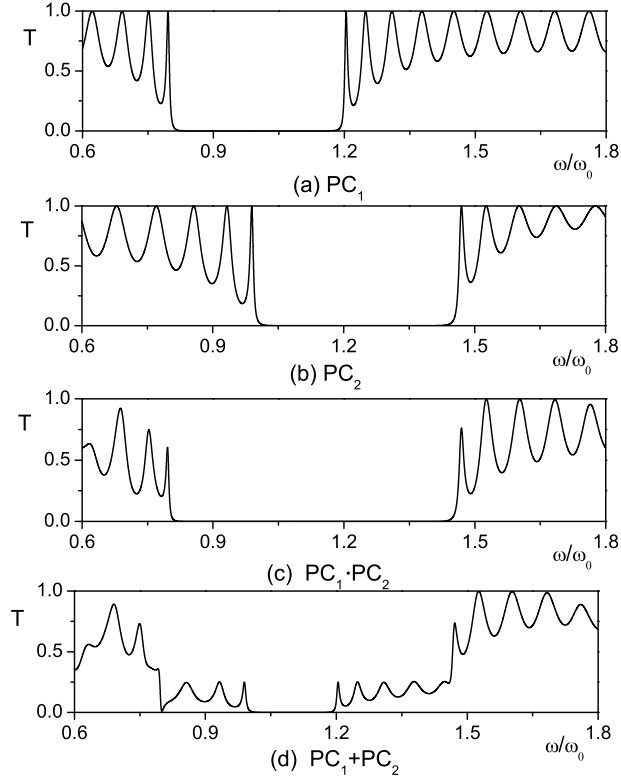


FIG. 3: The series connection structure transmissivity. (a) PC_1 transmissivity, (b) PC_2 transmissivity, (c) series connection transmissivity, (d) parallel connection transmissivity.

the defect mode frequency of PC. When the PC has the defect mode, transmissivity $T = 1$ corresponds to logical 1. When the PC has no defect mode, transmissivity $T = 0$ corresponds to logical 0. The logical AND operation are: $0 \cdot 0 = 0$, $1 \cdot 0 = 0$ and $1 \cdot 1 = 1$. In FIG. 4, the structures of PC_1 and PC_2 both are $(AB)^{12}$ with no defect mode. FIGs. 4 (a), (b) and (c) show the transmissivity corresponding to the structure PC_1 , PC_2 and $PC_1 \cdot PC_2$. PC_1 and PC_2 both correspond to logic 0. The series connection $PC_1 \cdot PC_2$ has transmissivity 0 corresponding to logic AND operation $0 \cdot 0 = 0$. In FIG. 5, the PC_1 is symmetrical structure $(AB)^6(BA)^6$ with the defect mode and PC_2 structure is $(AB)^{12}$ without the defect mode. FIGs. 5 (a), (b) and (c) show the transmissivity corresponding to the structure PC_1 , PC_2 and series connection $PC_1 \cdot PC_2$. PC_1 corresponds to logical 1. PC_2 corresponds to logical 0. The series connection $PC_1 \cdot PC_2$ has transmissivity 0 corresponding to logic AND operation $1 \cdot 0 = 0$. In FIG. 6, PC_1 and PC_2 both are symmetrical structure $(AB)^6(BA)^6$. They are both have defect mode. FIGs. 6 (a), (b) and (c) show the transmissivity corresponding to the structure PC_1 , PC_2 and $PC_1 \cdot PC_2$. At the working frequency, PC_1 and PC_2 both have transmissivity 1 corresponding to the logic 1. The series connection $PC_1 \cdot PC_2$ has transmissivity 1 corresponding to logic AND operation $1 \cdot 1 = 1$.

Finally, we will study the OR logical operation based on the parallel connection one-dimensional PC PC_1 and PC_2 . The logical OR operation are: $0 + 0 = 0$, $1 + 0 = 1$ and $1 + 1 = 1$, which correspond to FIGs. 7, 8 and 9, respectively. In FIG. 7, the structures of PC_1 and PC_2 both are $(AB)^{12}$. FIGs. 7 (a), (b) and (c) show the transmissivity corresponding to the structure PC_1 , PC_2 and $PC_1 + PC_2$ (the parameter $c_1 = 0.9$), they are all with no defect mode, correspond to logic 0, which realize the logical OR operation $0 + 0 = 0$. For FIG. 8 (a), the PC_1 is symmetrical structure $(AB)^6(BA)^6$ with the defect mode corresponds to logical

1, For FIG. 8 (b), the PC_2 structure is $(AB)^12$ without the defect mode corresponds to logical 0. The FIG. 8 (c) show the transmissivity corresponding to the parallel connection structure $PC_1 + PC_2$ with the defect mode corresponds to logical 1, which realize the logical OR operation $1 + 0 = 1$. In FIG. 9 (a) and (b), the PC_1 and PC_2 are symmetrical structure $(AB)^6(BA)^6$ with the defect mode corresponds to logical 1. FIG. 9 (c) is the transmissivity corresponding to the parallel connection structure $PC_1 + PC_2$ with the defect mode corresponds to logical 1, which realize the logical OR operation $1 + 1 = 1$.

5. Conclusion

In summary, we have proposed the compound structure one-dimensional PC, which include series connection and parallel connection compound structure. We have studied series connection and parallel connection transmission characteristics and obtained some new results. In addition, we have proved the series connection one-dimensional PC can realize the logical AND operation, and the parallel connection one-dimensional PC can realize the logical OR operation. We think the other logical operations can be achieved by other compound structure PC. The compound structure PC will help to design more new type structure optical devices, and provide the basic for designing quantum computer.

6. Acknowledgment

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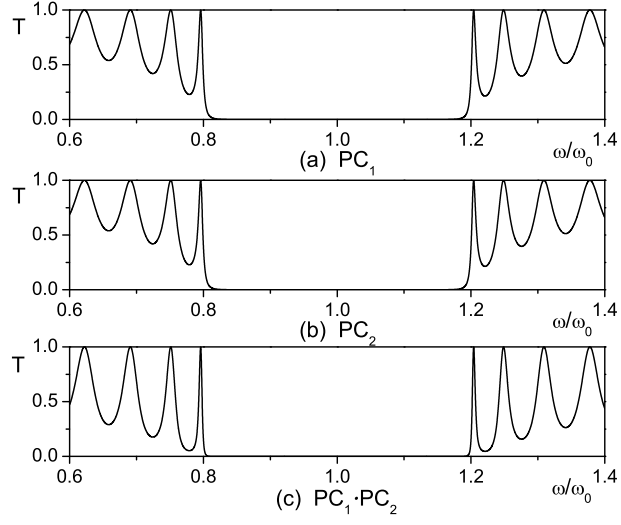


FIG. 4: The series connection structure transmissivity. (a) PC_1 transmissivity without defect model (logical 0), (b) PC_2 transmissivity without defect model (logical 0), (c) series connection transmissivity without defect model (logical 0), realizing logical AND operation $0 \cdot 0 = 0$.

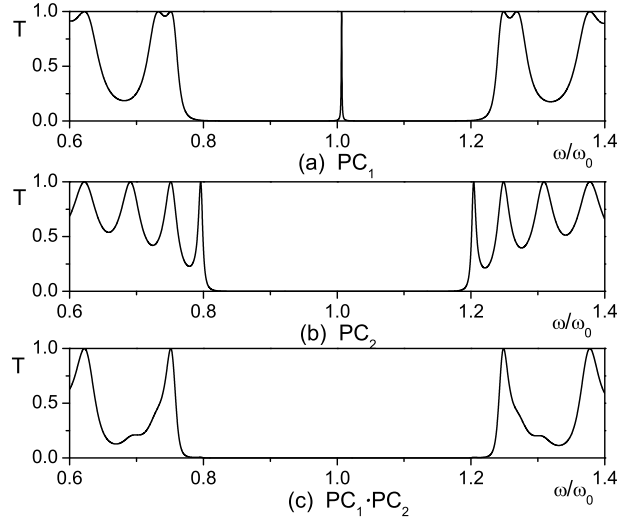


FIG. 5: The series connection structure transmissivity. (a) PC_1 transmissivity with defect model (logical 1), (b) PC_2 transmissivity without defect model (logical 0), (c) series connection transmissivity without defect model (logical 0), realizing logical AND operation $1 \cdot 0 = 0$.

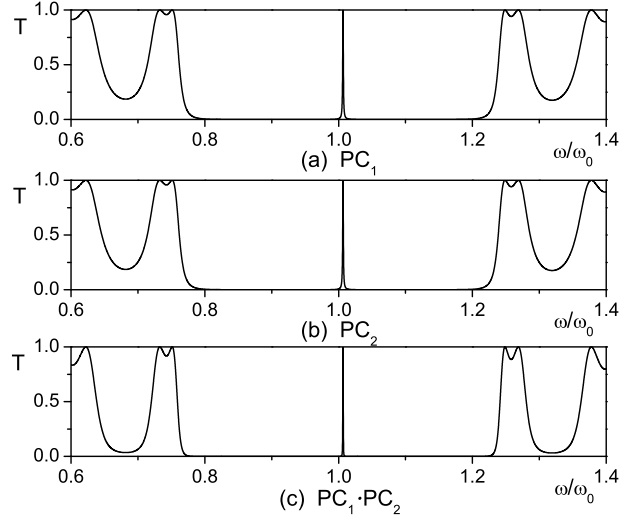


FIG. 6: The series connection structure transmissivity. (a) PC_1 transmissivity (logical 1), (b) PC_2 transmissivity (logical 1), (c) series connection transmissivity (logical 1, realizing logical AND operation $1 \cdot 1 = 1$).

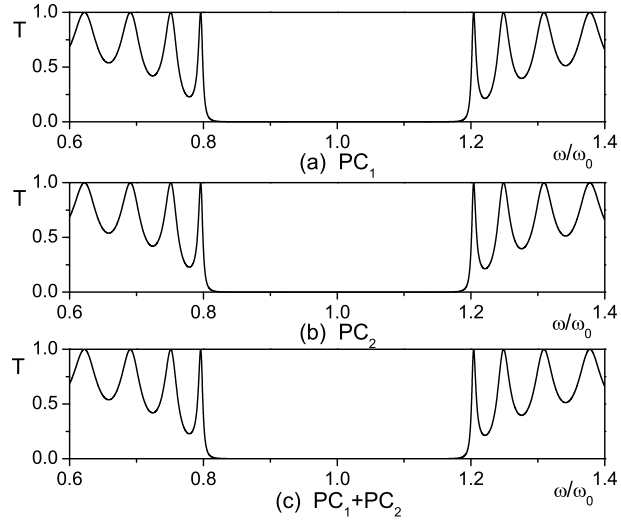


FIG. 7: The parallel connection structure transmissivity. (a) PC_1 transmissivity without defect model (logical 0), (b) PC_2 transmissivity without defect model (logical 0), (c) series connection transmissivity without defect model (logical 0), realizing logical OR operation $0 + 0 = 0$.

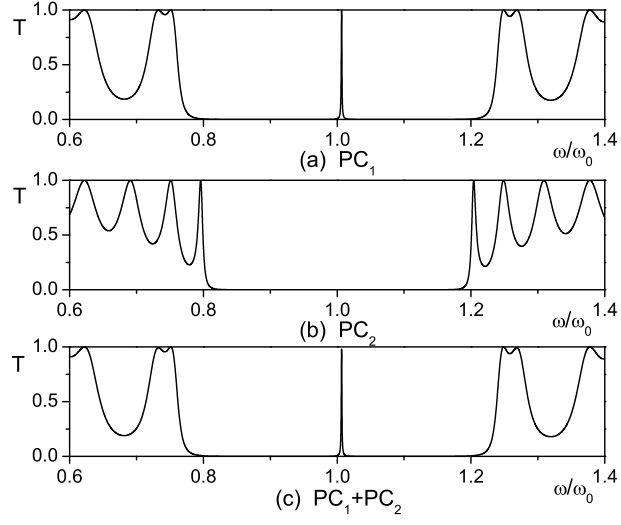


FIG. 8: The parallel connection structure transmissivity. (a) PC_1 transmissivity with defect model (logical 1), (b) PC_2 transmissivity without defect model (logical 0), (c) series connection transmissivity with defect model (logical 1), realizing logical OR operation $1 + 0 = 1$.

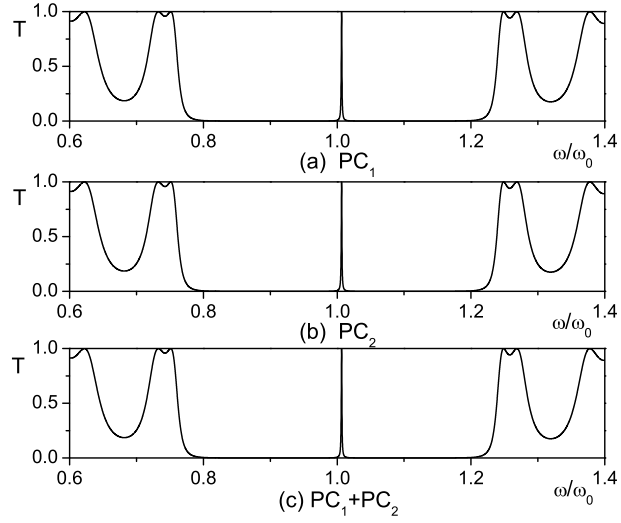


FIG. 9: The parallel connection structure transmissivity. (a) PC_1 transmissivity with defect model (logical 1), (b) PC_2 transmissivity with defect model (logical 1), (c) series connection transmissivity with defect model (logical 1), realizing logical OR operation $1 + 1 = 1$.